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A ROCKET-BORNE, LOW GRAVITY CRYOGENIC HEAT TRANSFER EXPERIMENT*

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ABSTRACT

In order to obtain steady state data on nucleate boiling heat transfer to liquid helium in a nearly zero gravity environment a rocket-borne experiment was designed, built and successfully flown. A description of the apparatus and flight is presented along with preliminary results.

INTRODUCTION

Although the space program is responsible for an interest in heat transfer to boiling cryogens in a reduced gravitational field, this phenomenon is also of fundamental interest. Previous experiments have utilized drop tower (1-2 sec experiments) [1], parabolic airplane flights (15 sec experiments) [2] and magnetic levitation [3,4]. These experiments were devoted to studies using liquid oxygen, liquid nitrogen (LN_2), or liquid hydrogen. No reduced gravity data exists for liquid helium (LHe).

The Q/A vs ΔT curve for a normal gravitation field of 1 g is shown in Fig. 1 for helium where Q/A is the heat flux in watts/cm^2 and ΔT is the temperature difference between the surface and the fluid in Kelvins. Helmholtz instability occurs at the peak nucleate heat flux point and is the result of vapor flowing away from the surface at a rate which destabilizes the flow of liquid to the surface. The result of this instability is a jump, at constant Q/A, in ΔT of one or more orders of magnitude depending upon the fluid used. This phenomenon is referred to as burnout since, with the more conventional fluids, tube walls could reach temperatures above their melting points. This seldom occurs with cryogenic systems because of the temperature level at which they are operated. Taylor instability occurs at the minimum heat flux point and is the result of an instability in the interfacial gas film. Instead of vapor alone contacting the heated surface the overriding dense liquid phase comes in contact with it changing the heat transfer mechanism from film to nucleate boiling.

The vast majority of maximum heat flux theories [5,6,7,8, 9,10,11] and minimum heat flux theories [5,12,13,14] includes a dependence of Q/A on $(a/g)^{1/4}$ where a is the component of acceleration in the direction of the gravitational field, g. In general the existing experimental data agrees with this dependence. One exception is the magnetic levitation work of Lyon et al. [4] using liquid oxygen. They found the 1/4 power dependence for accelerations ranging from approximately 0.25 to 1 g but only a 1/14 power dependence below 0.25 g.

Experimentally for LN_2 [1] and liquid hydrogen [2] it has been shown that nucleate boiling data (other than maximum heat flux) are not sensitive to gravity changes. From these results it has been concluded that bouyant forces are not significant in the process of nucleate boiling [1,2]. The primary influencing factor appears to be inertial forces. A Froude number criterion was introduced [15] to indicate the relative importance of inertial and bouyant forces. This number for nucleate boiling is the ratio of inertial to bouyant forces and is based upon bubble growth dynamics [16,17]. Values are given in Table 1 for helium, hydrogen, nitrogen and oxygen.

Table 1

FROUDE NO. AT 1 ATM AND 1 g

Liquid	Froude No.
Helium	0.020
Hydrogen	352
Nitrogen	452
Oxygen	546

For all of the fluids in Table 1, with the exception of helium, inertial forces far outweigh bouyant forces thus confirming theoretically the observations on hydrogen and nitrogen. In the case of helium, bouyant forces predominate at 1 g. As the g level decreases the Froude number increases reaching a value of 1 for He at 0.020 g's.

Because of this interesting difference of helium from other cryogens, the lack of steady state reduced gravity data and the lack of any reduced gravity helium data an experiment was conceived to utilize a free fall rocket trajectory to obtain 5.5 minutes of a nearly zero-g environment.

DESCRIPTION OF THE EXPERIMENT

The purpose of the experiment was to obtain steady state near zero-g nucleate boiling heat transfer data on two cryogenic fluids, LN_2 and LHe. In addition, it was hoped that some information would be obtained on the location and movement of the vapor bubble in each fluid.

The LN_2 served two purposes. The first was to provide thermal shielding for the LHe thus minimizing boiloff as a result of thermal radiation and conduction heat leaks. The second was to provide a control medium for comparison to existing, albeit nonsteady state data. Both cryogenic fluid containers were instrumented similarly. The heat transfer sensors (five in each container) consisted of 1/4-inch diameter cylindrical copper rods insulated on the sides and one end with 1/4-inch of polyurethane foam. A 100 ohm heater was wound around each rod at the end opposite the exposed end. Two thermistors were imbedded in the copper between the heater and the exposed end. The heat transfer surface temperature was obtained by extrapolating the measured temperatures to the exposed surface. Thermistors were also used to obtain bulk fluid temperatures at three locations in each vessel. The cryostat was equipped with a three axis accelerometer having a full scale reading of 0.05 g. Fluid pressures were obtained from one strain gage type pressure transducer on each vessel.

During the flight the Q/A values were stepped every 30 seconds for the first eight 30 sec time increments. From the ninth (last) step until the conclusion of the zero-g portion of the flight (90 sec) the Q/A values remained constant. The five values of Q/A for each fluid were chosen to cover the nucleate boiling region. The highest Q/A was chosen to be near the peak nucleate heat flux for 1 g. Typical Q/A values for the He and N_2 heat transfer sensors are shown in Table 2.

Table 2

TYPICAL POWER STEPS FOR TWO OF THE HELIUM AND TWO OF THE NITROGEN SENSORS

Programmer step	Q/A, W/cm^2 He (A)	He (B)	N_2 (A)	N_2 (B)
1	1.04	0.083	0.123	13.32
2	0.083	0.131	1.44	19.73
3	0.131	0.304	6.42	0.123
4	0.304	0.691	13.32	1.44
5	0.691	1.04	19.73	6.42
6	0.304	0.691	13.32	1.44
7	0.131	0.304	6.42	0.123
8	0.083	0.131	1.44	19.73
9	1.04	0.083	0.123	13.32

DESCRIPTION OF THE EQUIPMENT

A schematic diagram of the experimental package is shown in Fig. 2. The cryostat contained a LHe vessel within a thermal shield connected to a LN_2 vessel which was covered with multilayer aluminized Mylar in the surrounding vacuum. Each vessel had a two liter capacity and was constructed of copper. The bottom closure on each vessel was removable and had attached to it all of the instrumentation for the given fluid. The closure was made vacuum tight by using Cerroseal O-rings tightened to 35-inch-lb by a series of bolts on the circumference of the closure flange. The interior of each vessel contained longitudinal baffles which divided this space into eight equal volumes. These baffles performed two functions. One was to isolate the heat transfer sensors from one another and the second was to minimize residual fluid motion after despin of the rocket system.

Each of the vessels was equipped with two vents; one at the top which allowed venting on the ground prior to launch with the vessels full of cryogenic fluid and the second located in the geometric center of each vessel. An electronic circuit was developed based on carbon resistor level sensors and latching solenoid valves which opened the vent surrounded by the vapor bubble during the flight. This was to prevent venting of liquid regardless of the vapor bubble location.

Constant pressure was maintained on the cryogenic fluid by means of nominal 14.7 psia relief valves. The actual pressure was measured with strain gage pressure transducers located on each vessel.

The heat transfer sensors were located both parallel and perpendicular to the rocket axis. In each vessel they were located near the ends of the vessel close to the circumference.

The electronic circuitry utilized a 28 V battery supply. The thermistors were supplied with constant currents of 5 μa in LN_2 and 2 μa in LHe. The output voltages were amplified so that the maximum voltage measured was nearly five volts.

A mechanical commutator sampled the 126 amplified data channels ten times every second. Eight data channels were monitored continuously in real time during the flight. These channels provided complete data from helium heat sensor B as well as the bulk He temperature and pressure. The telemetered data were recorded on magnetic tape.

The 350 lb payload was launched in a 9-inch Nike-Tomahawk rocket. The payload was designed to withstand the launch loading of 30 g's and the deceleration of 5 g's between rocket stage firings. The payload was equipped with parachute and recovery beacon.

DESCRIPTION OF THE FLIGHT

The rocket and payload assembly were mounted on the launcher one day before the scheduled liftoff. The launch countdown began five hours before launch (T - 5 h) at 5:00 A.M. HST Wednesday, June 20, 1973, Barking Sands Missile Range, Kauai, Hawaii. At T - 90 minutes the filling of LN_2 and LHe commenced. The LHe fill was completed at approximately T - 45 minutes. On the launcher boiloff gases were vented through auxiliary solenoid valves held open with power supplied from the launcher. At liftoff this power was disconnected and these valves closed. At T + 62 sec (approximately 280,000 ft altitude) the on-board vent system was activated. Eighteen seconds after despin, at T + 82 sec (385,000 ft), the experiment was started with the arming of the sensor heaters. An apogee of 753,000 ft was achieved at T + 239 sec. At T + 412 sec the zero-g environment was lost as the payload began to encounter measureable atmospheric resistance. At T + 520 sec all electrical power was turned off to minimize salt water corrosion after splash-down, the parachute was deployed, a recovery beacon activated and within one-half hour the payload had been recovered from the ocean. The recovered package was in excellent, reusable condition.

RESULTS

It should be emphasized that the flight data reported herein are limited and of a preliminary nature. This is necessary since all of the nitrogen data and most of the helium data are available only from magnetic tape recordings of the flight data. Computer processing of these tapes and data analysis will require several months. The flight data reported was obtained from real-time visicorder records which were not setup for maximum data resolution.

Prelaunch tests showed that the heat leak to the helium vessel was 0.13 watts and to the nitrogen vessel 4.2 watts. With these heat leaks complete vaporization of the helium required 11 h and the nitrogen 15 h. Thus at launch both vessels were approximately 90% full. Throughout the flight the helium bath temperature was constant at 4.2 K which corresponds to a pressure of slightly under 1 atm absolute. The g level on all three axes was less than 0.005 g's.

Preliminary heat transfer results for two of the helium sensors are shown in Fig. 3. The first sensor had its surface parallel to the axis of rocket (vertical in the 1 g environment) near the circumference of the helium vessel. The results from this sensor at 1 g (▲) were in agreement with other helium data yielding a peak nucleate heat flux of approximately 1 W/cm^2 at a ΔT of approximately 0.6 K. At zero-g (◆) the peak nucleate heat flux was reduced by nearly an order of magnitude to approximately 0.11 W/cm^2. The second helium sensor had its surface perpendicular to the rocket axis (facing downward in the 1 g environment). It yielded a 1 g peak nucleate heat flux (●) of approximately 0.25 W/cm^2 which is considerably lower than accepted literature values. This may be attributed to the fact that for helium at 1 g, bouyant forces (Froude number of 0.02) predominate. Because of its downward configuration the surface of this sensor vapor locks under 1 g conditions thus reducing the maximum in (Q/A) and approximating the zero-g data (■). At 0.02 g the Froude number of helium has increased to one and inertia forces begin to dominate. In the region where bouyant forces dominate (greater than 0.02 g for helium) orientation of the surfaces is important with it apparently being possible to obtain zero-g data from a 1 g

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experiment. The arrows on the film boiling data points of Fig. 3 indicate that these points should lie at higher values of ΔT than plotted. The exact position of these points will not be known until the recorded data are computer processed.

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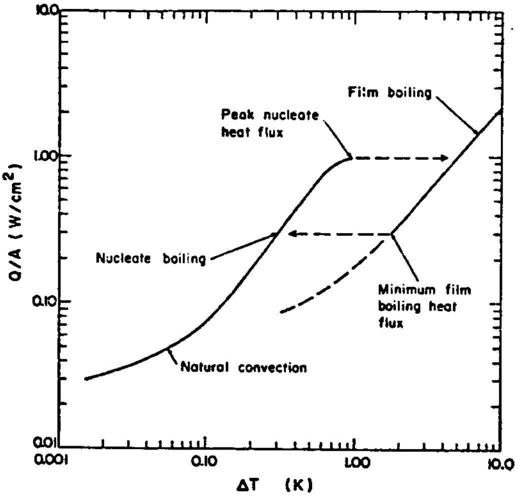

Fig. 1 - Q/A vs ΔT for helium at 1 g.

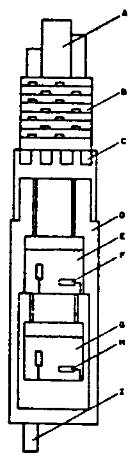

Fig. 2 - Schematic drawing of the experimental payload. A — programmer and commutator; B — printed circuit electronic boards; C — solenoid valves used for venting; D — vacuum space; E — liquid N_2; F — liquid N_2 heat transfer sensor; G — liquid He; H — liquid He heat transfer sensor; I — three axis accelerometer.

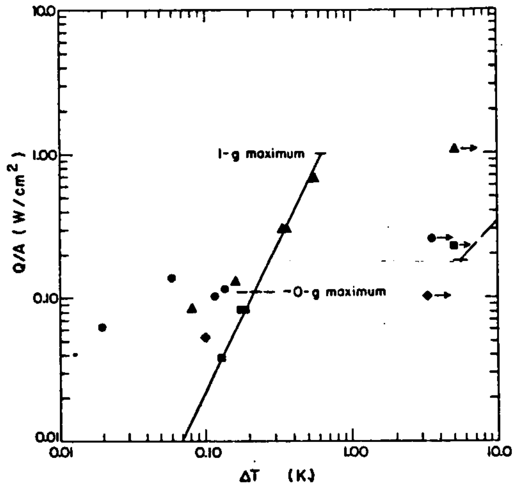

Fig. 3 - Preliminary experimental helium heat transfer. (▲) 1 g data with sensor surface parallel to rocket axis; (◆) zero-g data with sensor surface parallel to rocket axis; (●) 1 g data with sensor surface perpendicular to rocket axis facing downward; (■) zero-g data with sensor surface perpendicular to rocket axis facing downward. Solid lines represent typical 1 g helium data.